Direct radiative effect of an intense Mediterranean desert dust outbreak, based on NMMB/BSC-Dust model simulations: the case of 2 August 2012

A.Gkikas[1], V. Obiso[1], S. Basart[1], O. Jorba[1], C. Pérez García-Pando[2,3], N. Hatzianastassiou[4], S. Gassó[5] and J.M Baldasano[1,5]

[1]*Earth Sciences Department, Barcelona Supercomputing Center, Barcelona, Catalonia, 08034, Spain*

[2]*Department of Applied Physics and Mathematics, Columbia University, New York, New York, 10027, USA*

[3]*NASA Goddard Institute for Space Studies, New York, New York, 10025, USA*

[4]*Laboratory of Meteorology, University of Ioannina, Ioannina, Epirus, 45110, Greece*

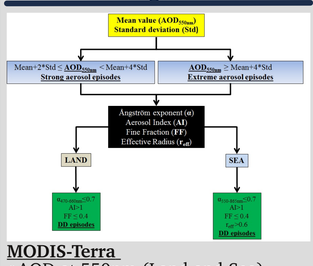
[5]*Environmental Modelling Laboratory, Technical University of Catalonia, Barcelona, Catalonia, 08034, Spain*

Corresponding author: Antonis Gkikas
e-mail: antonis.gkikas@bsc.es

Abstract

In summer, the western parts of the broader Mediterranean basin are frequently affected by intense desert dust outbreaks (Moulin et al., 1998). Massive dust loads, originating mainly in the western Sahara Desert, are transported under the prevalence of a southwestern airflow at 700hPa resulting from the combination of low (western Sahara) and high (Europe) pressure systems (Gkikas et al., 2014). Considering the high concentrations and the strong absorption efficiency of dust particles, it is expected that they will exert a significant perturbation of the Earth - Atmosphere system's radiation budget, since they interact both with the shortwave and longwave radiation. This interaction is made through direct, semi-direct and indirect processes. In the present analysis, we are making use of satellite observations and modelling simulations in order to investigate the direct radiative effects (DREs) induced by an intense desert dust outbreak that affected the southern parts of the Iberian Peninsula on 2nd August 2012.

Dust episodes



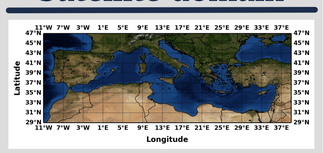
MODIS-Terra
- AOD at 550nm (Land and Sea)
- Ångström exponent (Land and Sea)
- Fine Fraction (Land and Sea)
- Effective radius (Sea)

EP-TOMS & OMI-Aura
- Aerosol Index (Land and Sea)

Satellite data

Study period: 1 March 2000 - 28 February 2013
Satellite domain: 11º W - 39º E, 29º N - 47º N
Satellite sensors: MODIS-Terra/Aqua (C051), Earth Probe - TOMS, OMI - Aura
Temporal resolution: Daily retrievals
Spatial resolution: 1º x 1º, 10km x 10km

Satellite domain



Selection of desert dust outbreaks

Desert dust (DD) episodes are identified in each 1° x 1° geographical cell of the Mediterranean domain based on an objective and dynamic algorithm, which is depicted in the flowchart (Gkikas et al., 2013). According to its outputs, for each day over the period 1/3/2000-28/2/2013 it is calculated the number of grid cells in which a DD episode has been recorded. Then, the days where the overall number of DD episodes is lower than 30 (Gkikas et al., 2014) are masked out. The remaining days are sorted based on their mean regional AOD_{550nm} and finally 20 days of the most intense dust outbreaks constitute the final dataset. In the present analysis, the case of 2nd August 2012 is studied.

NMMB/BSC - Dust model

The NMMB/BSC-Dust contains a dust module which is embedded online within the NCEP Non-hydrostatic Multiscale Model (NMMB). Thanks to its unified non-hydrostatic dynamical core it is able to provide weather and dust forecasts, from regional to global scales. The dust cycle is represented through several parameterizations describing dust particles' sources, emissions, transport, removal from the atmosphere (wet and dry deposition) as well as the interaction with the radiation (Pérez et al., 2011). After a 10-day spin-up period, model outputs every three hours for a 168h (7 days) forecasting period, for our case starting from 00 UTC of 2nd August 2012, using 1º x 1º NCEP final analyses (FNL) as initial and 6-h boundary conditions, are selected. The simulation domain covers the largest part of Europe as well as the northern African and Arabian Peninsula deserts, at 0.25° x 0.25° spatial resolution and for 40 hybrid sigma pressure levels up to 50hPa. Here, it is used the operational version of the NMMB/BSC-Dust model contributing to the first WMO Regional Meteorological Center specialized in Atmospheric Sand and Dust Forecast, the Barcelona Dust Forecast Center (BDFC; http://dust.aemet.es).

Direct Radiative Effect

The direct radiative effects (DREs) in the Earth-Atmosphere system are calculated based on the following formulas:

1. Top of Atmosphere (**TOA**)

$$DRE_{TOA} = F^{\uparrow}_{TOA,RADOFF} - F^{\uparrow}_{TOA,RADON}$$

2. Into the Atmosphere (**ATMAB**)

$$DRE_{ATMAB} = F_{ATMAB,RADON} - F_{ATMAB,RADOFF}$$

3. Downwelling radiation at surface (**SURF**)

$$DRE_{SURF} = F^{\downarrow}_{SURF,RADON} - F^{\downarrow}_{SURF,RADOFF}$$

4. Absorbed radiation at surface (**NETSURF**)

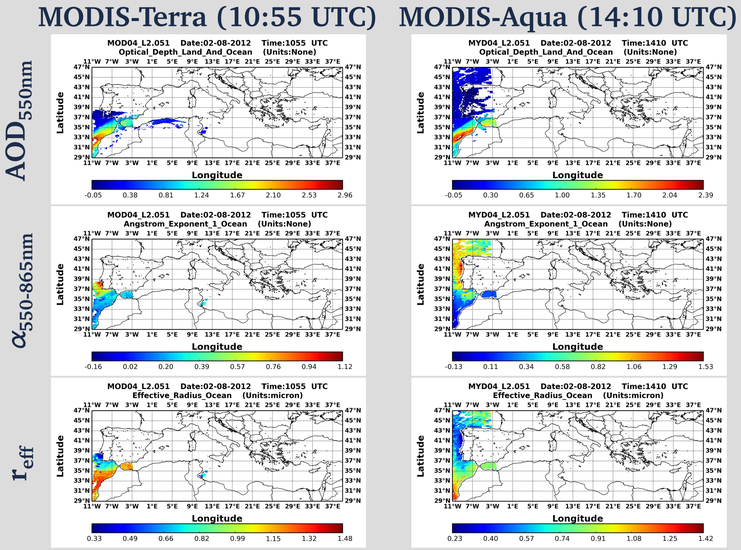
$$DRE_{NETSURF} = F_{NETSURF,RADON} - F_{NETSURF,RADOFF}$$

RADON: dust-radiation interaction
RADOFF: no dust-radiation interaction

Positive DREs indicate **warming** while **negative** DREs indicate **cooling**.

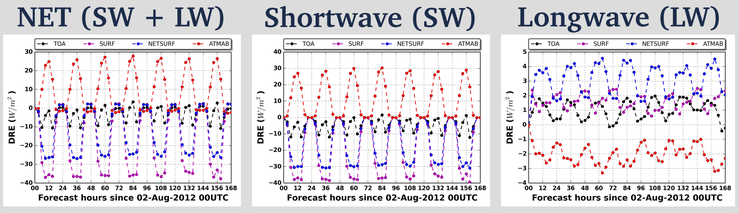
Results

Satellite observations (2 August 2012)



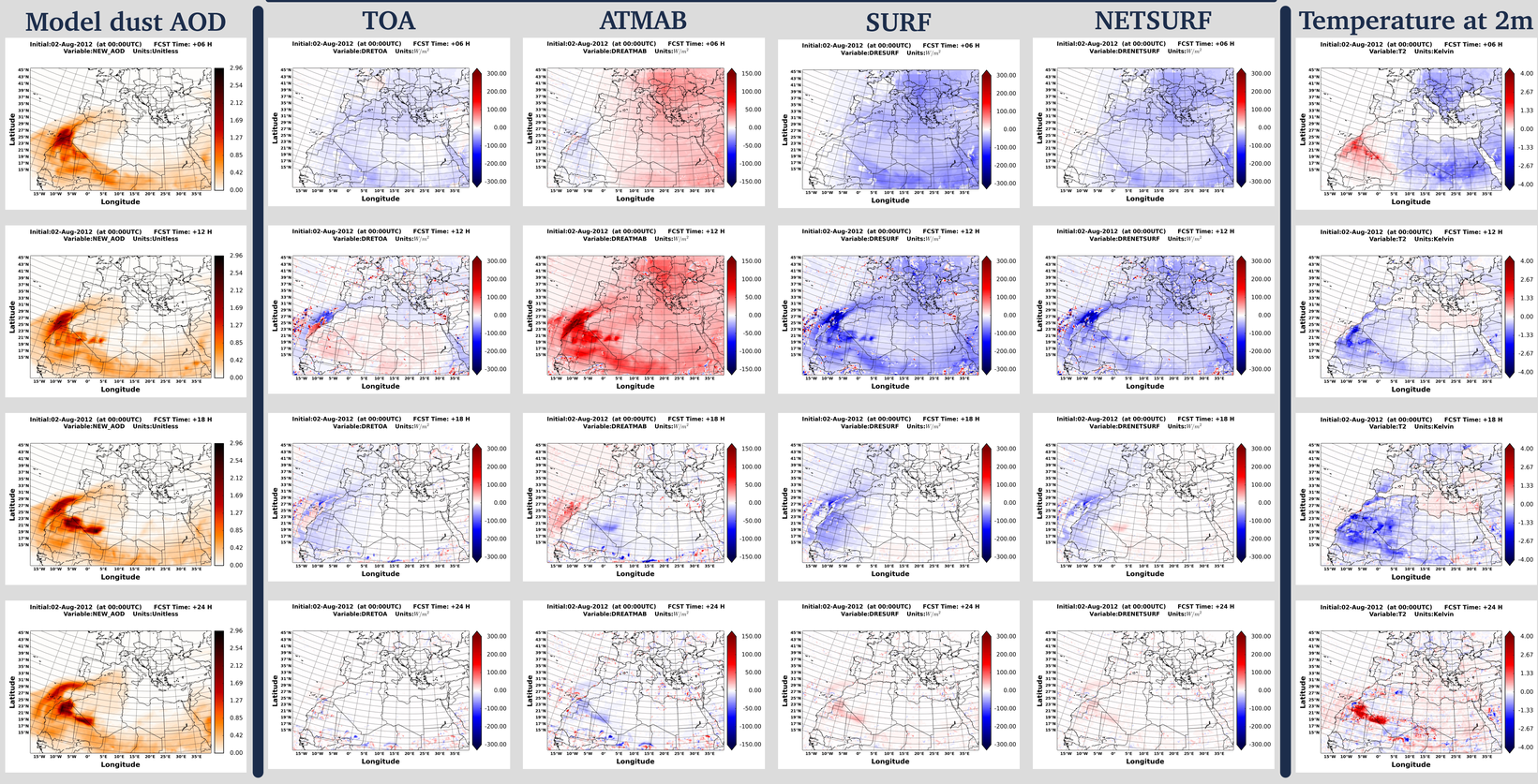
The desert dust outbreak was captured by the MODIS-Terra and MODIS-Aqua radiometers at 10:55 UTC and 14:10 UTC, respectively. From both sensors, we have plotted the AOD, $\alpha_{550\text{-}865nm}$ and r_{eff} Level 2 retrievals, which are provided at fine temporal (5mim) and spatial (10km x 10km) resolution. According to the satellite observations, at 10:55 UTC, the maximum AODs (close to 3) are recorded off the Moroccan coasts. At late noon (14:10 UTC), the dust plume reveals similar spatial characteristics but its intensity has been reduced down to 2.4. The predominance of coarse dust particles is confirmed by the low $\alpha_{550\text{-}865nm}$ (<0.4) and high (>0.8 μm) r_{eff} values in both platforms. Despite the generally good agreement between Terra and Aqua, a more detailed analysis reveals changes of aerosol optical properties in absolute terms, highlighting thus the diurnal variability of the desert dust outbreaks' characteristics.

Regional DREs



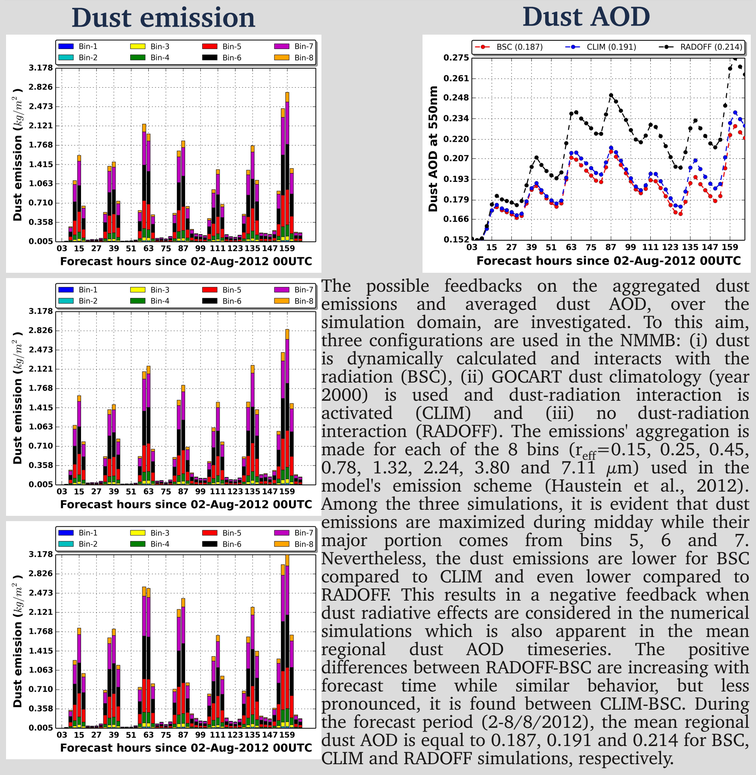
The regional DREs, averaged for the whole simulation domain, have been calculated for TOA, ATMAB, SURF and NETSURF, for the whole spectrum range (NET) as well as for the shortwave (SW) and longwave (LW) radiation. According to our results for the NET radiation, the atmospheric (ATMAB) heating and the surface (NETSURF) cooling by up to 30 Wm^{-2} and 25 Wm^{-2}, respectively, are maximized at noon. Depending on their absolute values, DRE_{TOA} can be slightly positive (warming) or negative (cooling). During nighttime, opposite DREs of low absolute values are found. The decrease of the downwelling radiation (DRE_{SURF}) at the ground can reach up to 40 Wm^{-2}. Slightly higher DREs are calculated for the SW radiation during daytime while in night hours are equal to zero. In the LW spectrum range, the impacts of dust aerosols are opposite and lower (less than 5 Wm^{-2} in absolute terms) than the corresponding ones for the SW radiation. Longwave radiative forcings are maximized around midday when dust particles induce a planetary (up to 2 Wm^{-2}) and surface warming (up to 4.5 Wm^{-2}) and an atmospheric cooling (up to 3 Wm^{-2}).

DREs



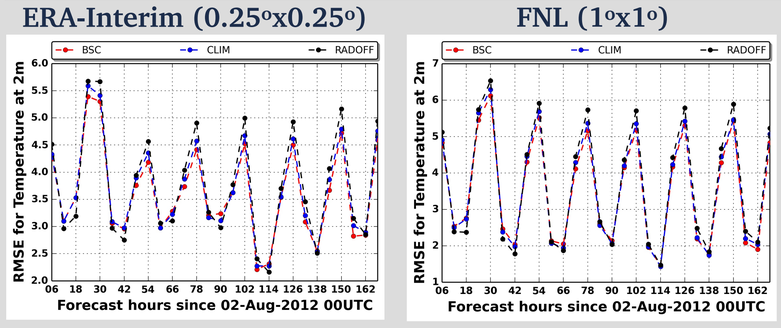
The geographical distributions of dust AOD_{550nm}, DRE_{TOA}, DRE_{ATMAB}, DRE_{SURF}, $DRE_{SURFNET}$ and the impact on air temperature at 2 meters, based on model simulations, are provided at +06, +12, +18 and +24h UTC referring to the first day (counting from the date and time of the identified dust outbreak) of the forecast period. According to model simulations, the dust storm originates across the northwestern parts of the Sahara while the arc shaped dust plume affects the Canary Islands, the southern parts of the Iberian Peninsula and the western Mediterranean Sea. AODs are maximized (up to 3) near to the source areas while considerably high values are recorded across the dust plume. The desert dust outbreak's impact on the radiation budget is clearly depicted in the net (SW+LW) DRE maps. At TOA, negative DREs by up to 250 Wm^{-2} are found in Canary Islands at +12h and +18h while during nighttime DRE_{TOA} values are almost zero in the dust affected areas. Into the atmosphere, it is evident the strong absorption of the solar radiation by dust particles at noon (DRE_{ATMAB} up to 185 Wm^{-2}) whereas there is a very good agreement between DRE_{ATMAB} and dust AOD spatial patterns. On the contrary, at late noon and night, negative DRE_{ATMAB} (down to -50 Wm^{-2}) are recorded in the areas where the dust AODs are maximized. Reverse impacts, compared to the atmosphere, are found at the surface. More specifically, mineral particles reduce (cooling effect) and increase (warming effect) the absorbed ($DRE_{NETSURF}$) allwave radiation at the surface during daytime and nighttime, respectively. The reduction of the net surface radiation can reach up to 300 Wm^{-2} while the increase up to 40 Wm^{-2}. Similar patterns but slightly higher absolute values are found for the DRE_{SURF}. Due to their direct interaction with the SW and LW radiation, dust particles reduce the surface temperature by up to 4º C during daytime while an increase of about the same magnitude it is found during night hours. These both lead to a reduction of the diurnal temperature range.

Feedbacks



The possible feedbacks on the aggregated dust emissions and averaged dust AOD, over the simulation domain, are investigated. To this aim, three configurations are used in the NMMB: (i) dust is dynamically calculated and interacts with the radiation (BSC), (ii) GOCART dust climatology (year 2000) is used and dust-radiation interaction is activated (CLIM) and (iii) no dust-radiation interaction (RADOFF). The emissions' aggregation is made for each of the 8 bins (r_{eff}=0.15, 0.25, 0.45, 0.78, 1.32, 2.24, 3.80 and 7.11 μm) used in the model's emission scheme (Haustein et al., 2012). Among the three simulations, it is evident that dust emissions are maximized during midday while their major portion comes from bins 5, 6 and 7. Nevertheless, the dust emissions are lower for BSC compared to CLIM and even lower compared to RADOFF. This results in a negative feedback when dust radiative effects are considered in the numerical simulations which is also apparent in the mean regional dust AOD timeseries. The positive differences between RADOFF-BSC are increasing with forecast time while similar behavior, but less pronounced, it is found between CLIM-BSC. During the forecast period (2-8/8/2012), the mean regional dust AOD is equal to 0.187, 0.191 and 0.214 for BSC, CLIM and RADOFF simulations, respectively.

Forecasting efficiency



At the last part of the analysis, are investigated possible improvements of the model's forecasting accuracy when dust radiative effects are considered in the numerical simulations. In order to address this issue, the 6-h forecast outputs of the temperature at 2 meters, based on the three model configurations (BSC, CLIM and RADOFF), are compared against the corresponding reanalyses data provided by ERA-Interim and FNL databases at 0.25ºx0.25º and 1ºx1º spatial resolution, respectively. At each forecast step, it is calculated the root mean square error (RMSE) between model outputs and reanalysis data for a sub-domain that comprises the arc shaped dust plume. According to the comparison results, it is evident that the model reproduces better the maximum (lower RMSEs) than the minimum (higher RMSEs) temperatures. Moreover, the performance of the model versus ERA-Interim is better for the minimum temperatures while against FNL a better agreement is found for the maximum ones. The most important finding from these preliminary results, is the decrease of the RMSE values, particularly for BSC simulation, during nighttime indicating thus an improvement of the model's forecasting efficiency, when dust radiative effects are included in the simulations. This has been also pointed out by Pérez et al., (2006) who conducted a similar analysis but for the mean sea level pressure.

Conclusions

- A desert dust outbreak that took place at 2nd August 2012 affected the western Sahara, the Canary Islands and the southern parts of the Iberian Peninsula.
- The desert dust outbreak has been identified based on an objective and dynamic algorithm, which uses as inputs a group of daily satellite retrievals provided at 1ºx1º spatial resolution.
- According to fine resolution (10km x 10km) MODIS observations, AOD and r_{eff} reached up to 3 and 1.5 μm, respectively, while alpha values were decreased down to -0.16, indicating the existence of coarse dust particles.
- DREs have been estimated based on NMMB/BSC-Dust model simulations for the period 2-8/8/2012.
- At a local scale, during midday, for the net radiation, it is estimated an instantaneous planetary and surface cooling by up to 250 Wm^{-2} and 300 Wm^{-2}, respectively, and an atmospheric warming by up 185 Wm^{-2}.
- On a mean regional scale (simulation domain), the net DRE_{TOA}, DRE_{ATMAB}, $DRE_{NETSURF}$ and DRE_{SURF} can reach up to -10 Wm^{-2}, 30 Wm^{-2}, -28 Wm^{-2} and -40 Wm^{-2}, respectively.
- Reverse but substantially lower DREs are found during nighttime and for the LW radiation.
- In the dust affected areas, the temperature at 2 meters can be decreased by 4º C during midday while an increase of the same magnitude is recorded during nighttime.
- Negative feedbacks on dust emissions and mean regional dust AOD are found when dust radiative effects are considered in the simulations.
- The consideration of dust radiative effects improves the ability of the model to reproduce the minimum temperatures.

European Aerosol Conference (EAC 2015)
6-11 September 2015
Milan, Italy

Acknowledgements

The MDRAF project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 622662.

CICYT Project (CGL2013-46736) and Severo Ochoa (SEV-996 2011-00067) programme of the Spanish Government.

References

Gkikas et al. (2013): The regime of intense desert dust episodes in the Mediterranean based on contemporary satellite observations and ground measurements, Atmos. Chem. Phys., 13, 12135-12154, doi:10.5194/acp-13-12135-2013.

Gkikas et al. (2014): Atmospheric circulation evolution related to desert-dust episodes over the Mediterranean. Q.J.R. Meteorol. Soc. doi: 10.1002/qj.2466.

Haustein et al. (2012): Atmospheric dust modeling from meso to global scales with the online NMMB/BSC-Dust model – Part 2: Experimental campaigns in Northern Africa, Atmos. Chem. Phys., 12, 2933-2958, doi:10.5194/acp-12-2933-2012.

Moulin et al. (1998): Satellite climatology of African dust transport in the Mediterranean atmosphere, J. Geophys.Res., 103, 13137–13144.

Pérez et al. (2006): Interactive dust-radiation modeling: A step to improve weather forecasts, J. Geophys. Res., 111, 1–17, 2006.

Pérez et al. (2011): Atmospheric dust modeling from meso to global scales with the online NMMB/BSC-Dust model – Part 1: Model description, annual simulations and evaluation, Atmos. Chem. Phys., 11, 13001-13027, doi:10.5194/acp-11-13001-2011.